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Supernova Neutrino Physics with Xenon Dark Matter Detectors

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Abstract. The dark matter experiment XENON1T is operational and sensitive to all flavors of neutrinos emitted from a supernova. We show that the proportional scintillation signal (S2) allows for a clear observation of the neutrino signal and guarantees a particularly low energy threshold, while the backgrounds are rendered negligible during the SN burst. XENON1T (XENONnT and LZ; DARWIN) will be sensitive to a SN burst up to 25 (40; 70) kpc from Earth at a significance of more than 5σ, observing approximately 35 (123; 704) events from a 27 $M_\odot$ SN progenitor at 10 kpc. Moreover, it will be possible to measure the average neutrino energy of all flavors, to constrain the total explosion energy, and to reconstruct the SN neutrino light curve. Our results suggest that a large xenon detector such as DARWIN will be competitive with dedicated neutrino telescopes, while providing complementary information that is not otherwise accessible.

1. Introduction

Core collapse supernovae (SNe) are among the most energetic transients that occur in the universe, originating from the death of very massive stars. A high-statistics detection

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of neutrinos from the next Galactic SN explosion in detectors that operate with different technologies will shed light on both the stellar engine and the properties of neutrinos. Neutrino flavour discrimination will be crucial to investigate neutrino oscillation physics and scenarios with non-standard neutrino properties. On the other hand, the detection of all six neutrino flavours will be essential to reconstruct global emission properties.

The elastic scattering of neutrinos on protons [1, 2] and on nuclei [3] are alternative tools to detect astrophysical neutrinos. Neutrino-nucleus scattering is especially attractive because, at low energies, the scattering cross section is coherently enhanced by the square of the nucleus's neutron-number. Supernova neutrinos with energies of $\mathcal{O}(10)$ MeV induce $\mathcal{O}(1)$ keV nuclear recoils through coherent elastic neutrino-nucleus scattering (CEνNS). Although recoils in this energy range are too small to be detected by conventional neutrino detectors, it is precisely this energy range for which direct detection dark matter experiments are optimized. The primary purpose of these experiments is to search for nuclear recoils induced by Galactic dark matter particles. Yet, sufficiently large experiments ($\gtrsim$ tonne of target material) are also sensitive to CEνNS from SN neutrinos [4, 5, 6, 7].

Mediated by Z-boson exchange, CEνNS is especially intriguing because it is equally sensitive to all neutrino flavours. Detectors that observe CEνNS are therefore sensitive to the $\bar{\nu}_\mu$, ν_μ, $\bar{\nu}_\tau$ and ν_τ (otherwise dubbed ν_x) neutrinos within their main detection channel, in addition to the $\bar{\nu}_e$ and ν_e neutrinos [3]. This feature carries numerous implications for experiments that detect CEνNS. For instance, the neutrino light curve could be reconstructed without the uncertainties that arise from neutrino oscillation in the stellar envelope, the total energy emitted into all neutrino species could be measured, or, by assuming adequate reconstruction of the $\bar{\nu}_e$ and ν_e emission properties with other detectors, CEνNS detectors provide a way to reconstruct the ν_x emission properties.

In this article [8], we revisit the possibility of detecting CEνNS from SN neutrinos in the context of XENON1T [9] and larger forthcoming direct detection dark matter experiments that employ a xenon target, such as XENONnT [9], LZ [10], and DARWIN [11]. Among the various technologies used in direct detection experiments, dual-phase xenon experiments have many advantages: the large neutron-number of the xenon nucleus enhances the CEνNS rate compared to nuclei used in other direct detection experiments; they are sensitive to sub-keV nuclear recoils; the deployment of XENON1T heralds the era of tonne-scale experiments, which are relatively straightforward to scale to even larger masses; despite their large size, the background rates are very low; and, finally, they have excellent timing resolution in the data analysis mode discussed here.

2. Supernova neutrino scattering with dual-phase xenon detectors

With the launch of the XENON1T experiment, direct detection dark matter searches have entered the era of tonne-scale targets. The detection principle of this experiment is similar to its smaller predecessors, including LUX [12], PandaX [13], XENON100 [14], XENON10 [15], and the three ZEPLIN experiments [16, 17, 18].

These experiments consist of a dual-phase cylindrical time projection chamber (TPC) filled primarily with liquid xenon and a gaseous xenon phase on top. The energy deposited by an incident particle in the instrumented volume produces two measurable signals, called the S1 and S2 signals, respectively, from which the energy deposition can be reconstructed. An energy deposition in the liquid xenon creates excited and ionized xenon atoms, and the prompt de-excitation of excited molecular states yields the S1 (or prompt scintillation) signal. An electric drift field of size $\mathcal{O}(1)$ kV/cm draws the ionization electrons to the liquid-gas interface. A second electric field of size $\mathcal{O}(10)$ kV/cm extracts the ionization electrons from the liquid to the gas. Within the gas phase, these extracted electrons collide with xenon atoms to produce the S2 (or proportional scintillation) signal. The S1 and S2 signals are observed with two arrays of photomultiplier tubes (PMTs) situated at the top and bottom of the TPC. A measurement of both the S1 and S2 signals allows for a full 3D reconstruction of the position of the energy deposition in the TPC. In typical dark matter searches, only an inner volume of the xenon target is used to search for dark matter (the "fiducial volume"), but the background rate for the duration of the SN signal is sufficiently small that all of the instrumented xenon can be used to search for SN neutrino scattering.

The general expression for the differential scattering rate dR in terms of the observable S1 and S2 signals for a perfectly efficient detector is

$$\frac{d^2R}{d\mathrm{S1}d\mathrm{S2}} = \int dt_{\mathrm{pb}} dE_{\mathrm{R}}\, \mathrm{pdf}\,(\mathrm{S1}, \mathrm{S2}|E_{\mathrm{R}})\, \frac{d^2R}{dE_{\mathrm{R}}dt_{\mathrm{pb}}}. \tag{1}$$

The differential rate is an integral over the time-period of the SN neutrino signal, expressed in terms of the post-bounce time t_{pb}, and an integral over the recoil energy E_{R} of the xenon nucleus. The differential scattering rate in terms of E_{R} is convolved with the probability density function (pdf) to obtain S1 and S2 signals for a given energy deposition E_{R}.

3. S2-only analysis

The canonical dark matter search in a dual-phase xenon experiment requires the presence of both an S1 and an S2 signal. This stipulation reduces the background rate based on the ratio S2/S1 and fiducialization, but it also significantly reduces the rate of low-energy nuclear recoils compared to an S2-only analysis. For SN neutrinos, however, the brevity of the $\mathcal{O}(10)$ s burst enables the signal to be discrimination from background based on the timing information rather than the S2/S1 ratio.

Although the low-energy S2 background in dual-phase xenon experiments is not yet fully understood, the dominant contribution is believed to arise from photoionization of impurities in the liquid xenon and on the metal surfaces in the TPC, which was found to cause single-electron emission in ZEPLIN-II [19], ZEPLIN-III [20], and XENON100 [21]. Another background contribution may be delayed extraction of electrons from the liquid to the gas phase [19]. Such processes create clusters of single-electron S2 signals and, occasionally, these single-electron signals overlap and appear as a single S2 signal from multiple electrons. The resultant low-energy background S2 signals are very similar to those expected in the case of a SN neutrino interaction. The background rate for these lone-S2 events has been characterized by XENON10 [22, 23] and XENON100 [24] and found to be negligible.

4. Detection Significance

We investigate the sensitivity of present and upcoming xenon detectors to a SN burst as a function of the SN distance from Earth, finding that XENON1T will be able to detect a SN burst at more than 5σ significance up to 25 kpc from Earth, while XENONnT and LZ will make at least a 5σ discovery anywhere in the Milky Way. DARWIN's much larger target mass will extend the sensitivity to a 5σ discovery past the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC).

In this investigation, the SN signal has been integrated over the first 7 seconds after the core bounce. We calculate the detection significance following the likelihood-based test for the discovery of a positive signal described in [25]. The null hypothesis is that the observed events are only due to the background processes described previously, while our alternative hypothesis is that the observed events are due to both the background processes and from SN neutrino scattering. A detection significance of 5σ means that we reject the background-only hypothesis at this significance, which we therefore regard as a 5σ discovery of the SN neutrino signal.

5. Outlook

With the launch of XENON1T and the plans for larger experiments employing the same technology, such as XENONnT, LZ, and DARWIN, we have demonstrated the possibility of detecting a Galactic supernova (SN) through coherent elastic neutrino-nucleus scattering (CEνNS) with such dual-phase xenon direct detection dark matter experiments [8]. Focusing on the S2 channel maximizes the number of events that can be detected. Due to a negligible background rate, high-significance discoveries can be expected.

For a SN burst at 10 kpc, features of the neutrino signal such as the neutronization burst, accretion phase, and Kelvin-Helmholtz cooling phase will be distinguishable with the DARWIN experiment. In addition, with DARWIN it will be possible to make a high-precision reconstruction of the average neutrino energy and differential neutrino flux. Since CEνNS is insensitive to the neutrino flavour, the signal in dual-phase xenon detectors is unaffected by uncertainties from neutrino oscillation physics. A high-precision measurement of CEνNS from SN neutrinos will therefore offer a unique way of testing our understanding of the SN explosion mechanism. The sensitivity to all neutrino flavours also means that it is straightforward to reconstruct the total energy emitted into neutrinos. At the same time, being flavour blind, dual-phase xenon detectors will provide complementary information on the SN neutrino signal that is not obtainable with existing or planned neutrino telescopes.

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